3D geometry and kinematics of the N. V. Turkse Shell thrustbelt oil fields, Southeast Turkey

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ABSTRACT

In 1984 NV Turkse Shell (NVTS) acquired the first 3D survey in Turkey, over the Beykan field. Between 1989 and 1992 an additional seven 3D surveys have been acquired. The 3D seismic data has enabled substantial advances in the understanding of detailed subsurface structure, deformational history and the relationships between oilfields. As a consequence, 3D results have led to fundamental revisions of structural maps in both heavily drilled (Beykan) and lightly explored (foreland, Kayakoy West Deep) areas. This work has provided a detailed picture of the lateral extent, internal geometry and hydrocarbon distribution within the major structures of the NVTS Lease Areas. The relationship between stacked imbricate structures, and the geometry of the underlying foreland setting has also been mapped in detail.

The classical view of the genesis of the SE Turkey Foothills Belt is that the terranes presently incorporated in the imbricated zone formed a positive (forebulge) area at the Arabian Platform edge in the Cretaceous. During the Late Cretaceous, coeval with Upper Mardin and Kastel Formation deposition, the platform edge was significantly deformed ultimately leading to imbrication. The resulting structures are typical examples of imbricates formed in a foreland setting. Thrust sheets are relatively thin, comprising a layered sedimentary sequence, and have a length which is several times greater than their thickness. The basal decollement plane formed in argillaceous units within the Silurian Dadas Formation. In the west, thrust imbricates are relatively thin and gentle folding accompanied thrusting. In the east the imbricates are much thicker and larger amplitude folding led to steeper dips in the deformed strata. In the area occupied by the Kurkan, Kayakoy and Kayakoy West structures, deformation resulted in a stack of smaller imbricates. These differences are caused by 1) the presence, in the east, of a clastic sequence overlying the argillaceous units of the Dadas Formation and 2) the resulting difference in frictional behaviour along the basal slip plane.

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INTRODUCTION

Since the discovery of relatively small and complex oil fields in the Foothills Belt of the Taurus Mountains in SE Turkey (Fig. 1), this area has been the subject of extensive geological and geophysical surveys. Using a variety of tools, a considerable number of additional structures have been identified and successfully drilled. A complete understanding of the relationship between individual structures has, however, remained elusive. The acquisition of 3D seismic data within the NV Turkse Shell Lease Areas has enabled substantial advances in the understanding of detailed subsurface structure, deformational history and relationships between fields. The results have had a significant impact upon the interpretation of the hydrocarbon habitat in the Foothills Belt, from migration path to fluid contacts, and will provide a basic framework for future reservoir characterisation work.

This paper concentrates upon the mechanics and kinematics of deformation and resultant subsurface geometry together with the implications for exploration and development activity in this densely drilled but still only partially understood area.

NVTS THRUSTBELT EXPLORATION AND 3D SEISMIC HISTORY

NV Turkse Shell (NVTS) has been actively exploring in Turkey since 1953. In 1960 the Kayakoy-2 well discovered the first commercial oilfield in the Foothills Belt (Fig. 2). Subsequently 300 wells have been drilled by NVTS in this structural setting resulting in the discovery of 26 fields. Exploration and development has employed a variety of tools over this period, including gravity surveying, 2D reflection seismic, refraction seismic, 2D swath acquisition, borehole gravimetry and recently 3D seismic. Progress in improving subsurface structural definition has been irregular, largely in step with incremental advances in geophysical technology.

The delineation of the major structures within the NVTS Lease Areas was largely established by combining drilling results with gravity and seismic data and surface geology studies. Some 10 years after the first discovery, the major structural elements (Beykan, Kurkan; Fig. 2) had been located, the variation in structural style across the Lease Areas described in general terms, the decollement level identified and the timing of the main phases of deformation established.

The various historical exploration methods employed, while adequate to map out the overall shape of most of the producing structures (Fig. 3), largely failed to delineate both the steeper southern flanks and the internal complexities of the imbricate sheets. Considerable uncertainty in the position of the southern boundary (thrust) fault in several fields hampered the optimal development of the crestal and leading edge areas of a number of accumulations.

In 1984 NVTS acquired the first 3D sesmic survey in Turkey, the 90 km^2 Beykan survey over the western and central parts of the field. Between 1989 and 1992 an additional seven 3D surveys have been acquired, all but two within the Foothills Belt setting (Fig. 4).

This paper summarises the results of initial seismic interpretation work involving four 3D surveys, 14 fields and some 220 wells. Work concentrated primarily upon the Cretaceous Mardin Group resrvoir sequence. Structural interpretation made extensive use of horizon attribute analysis (dip/azimuth) in combination with fault data from well penetrations.

STRUCTURAL SETTING AND REGIONAL STRATIGRAPHY

The Taurus Mountain Belt represents a zone of major Alpine deformation which formed in response to the collision of the Arabian Platform and Eurasia (Fig. 5; Sengör and Yilmaz, 1981; Yilmaz, 1993). The zone can be subdivided: (Fig. 6):

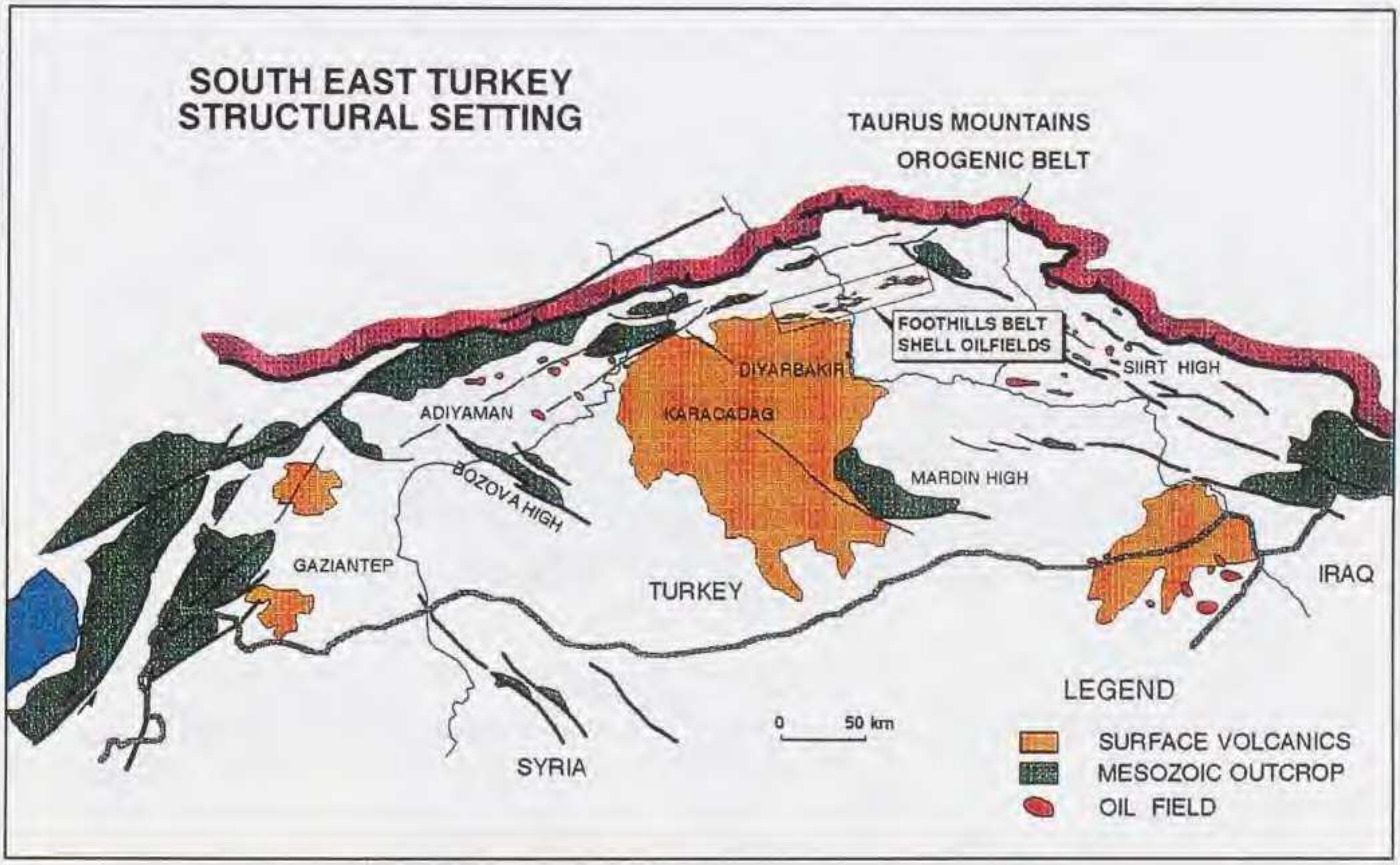

FIG. 1.

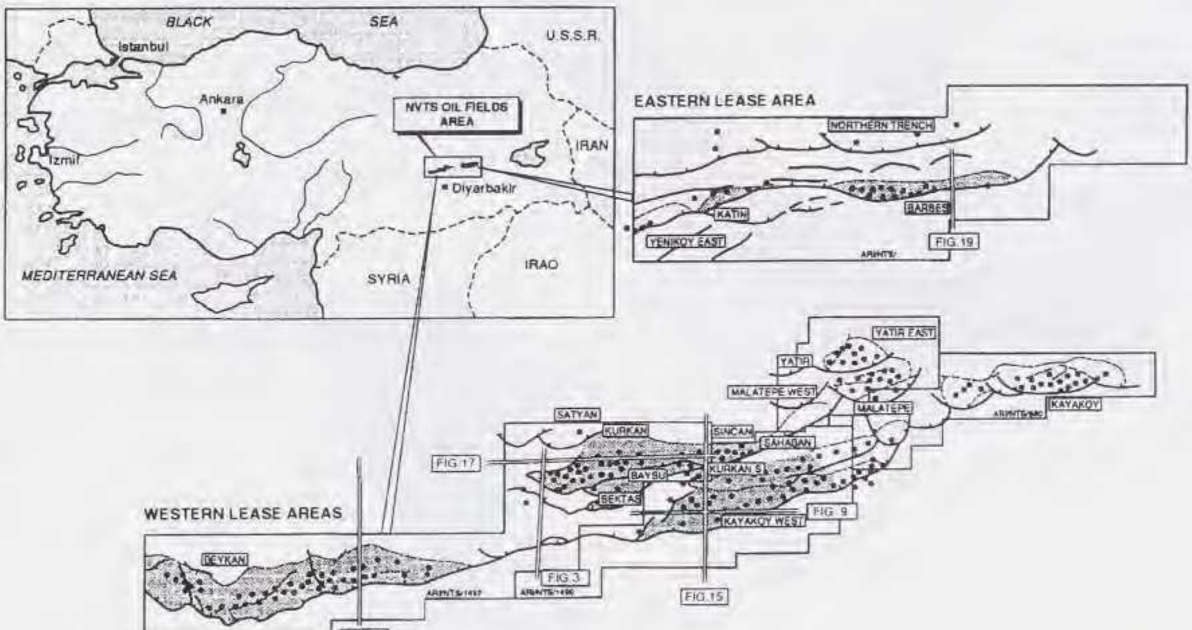

FIG. 2 Location map of NVTS lease areas

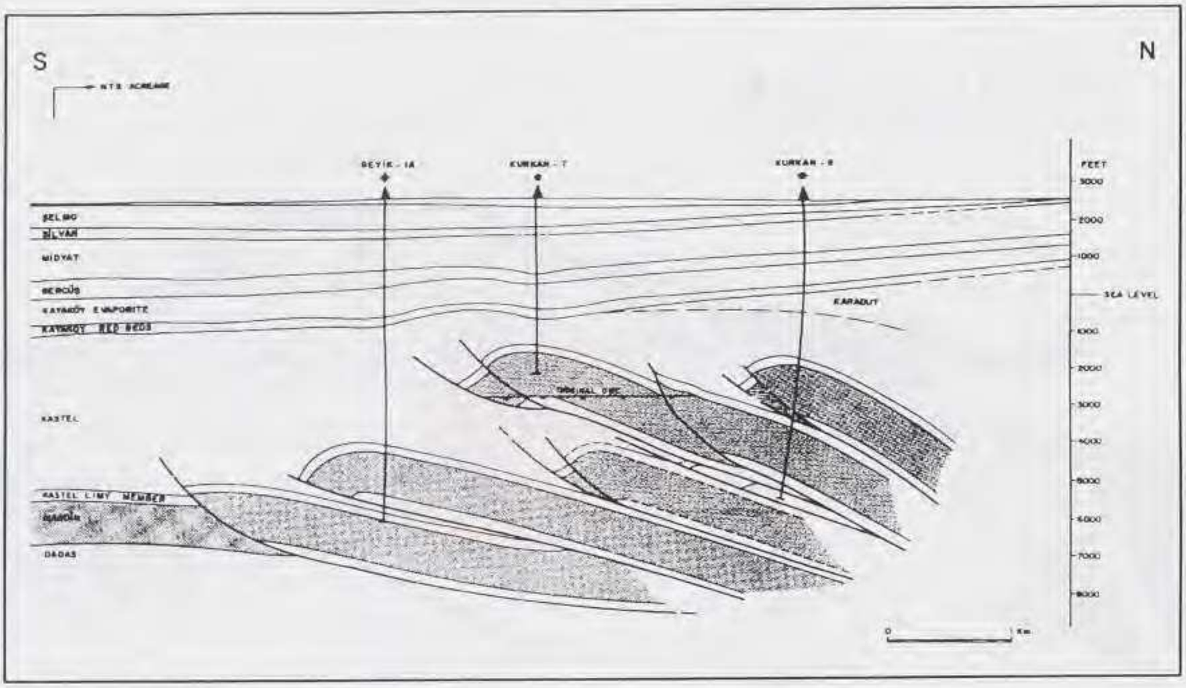

FIG. 3. Geological cross-section, Western Lease Areas

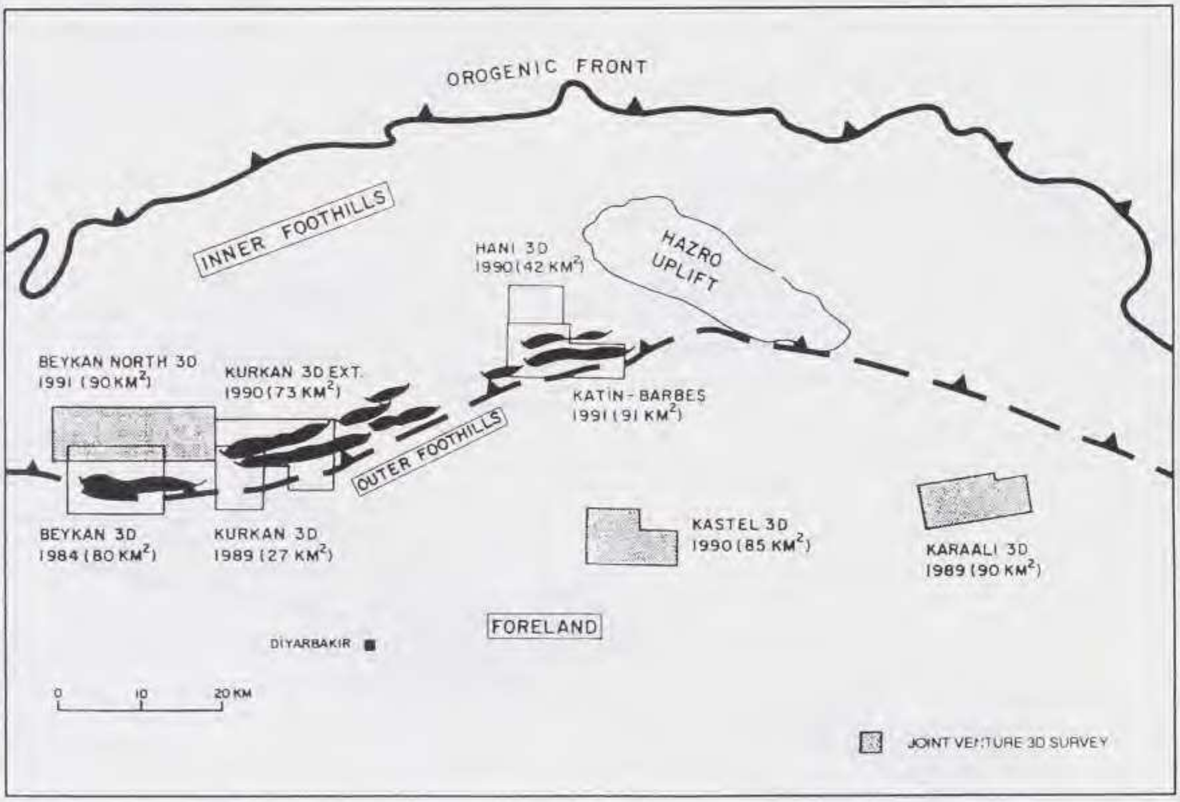

FIG. 4. NV Turkse Shell 3D activity

(1) Orogenic Belt characterised by large scale uplift and nappe tectonics,
(2) Foothills Belt characterised by imbricate thrusting and disharmonic folding,
(3) Foreland characterised by gentle folding and normal and reverse faulting.

Pre-deformation, the areas presently incorporated within the Foothills Belt and the Foreland were situated on the northern margin of the Arabian Platform, where during much of the Cretaceous (Upper Aptian to Lower Campanian), platform carbonates were deposited. The collision of the Arabian Platform with Eurasia, initiated during the Late Cretaceous, led to the formation of the elongated Kastel trough coupled with a forebulge ahead of advancing ophiolitic nappes (Fig. 7a; Horstink, 1971). The foredeep rapidly filled with marls and shales of the Kastel Formation (Fig. 7b) which also contains abundant clasts of both ophiolitic and platform carbonate associations. The latter represent erosional products derived from the forebulge which, under the influence of the advancing nappes, was subsequently rapidly submerged. Consequently, shallow marine Kastel deposits now overlie the upper Mardin erosional surface (Fig. 7c).

Continued compression transmitted by the ophiolitic nappes advancing over the platform sediments, resulted in the imbrication and overthrusting to the south of the foredeep sediments and their basement. Basal thrusts are primarily developed in relatively incompetent Palaeozoic sediments and cut up-section through the more competent Mardin Group rocks. The southern edge of the thrustbelt coincides with the original forebulge area and marks the boundary between the Foothills Belt and the Foreland.

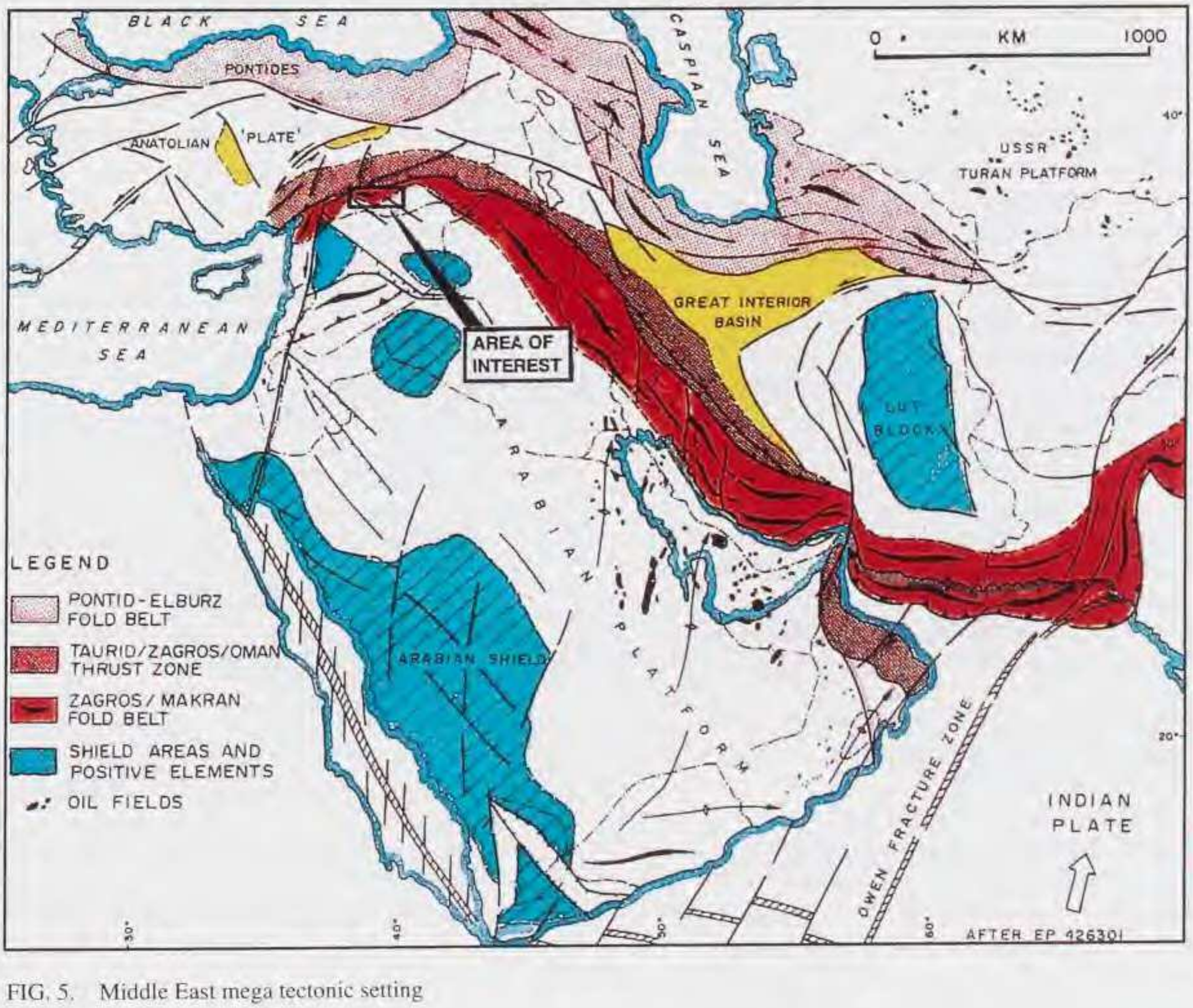

FIG. 5. Middle East mega tectonic setting

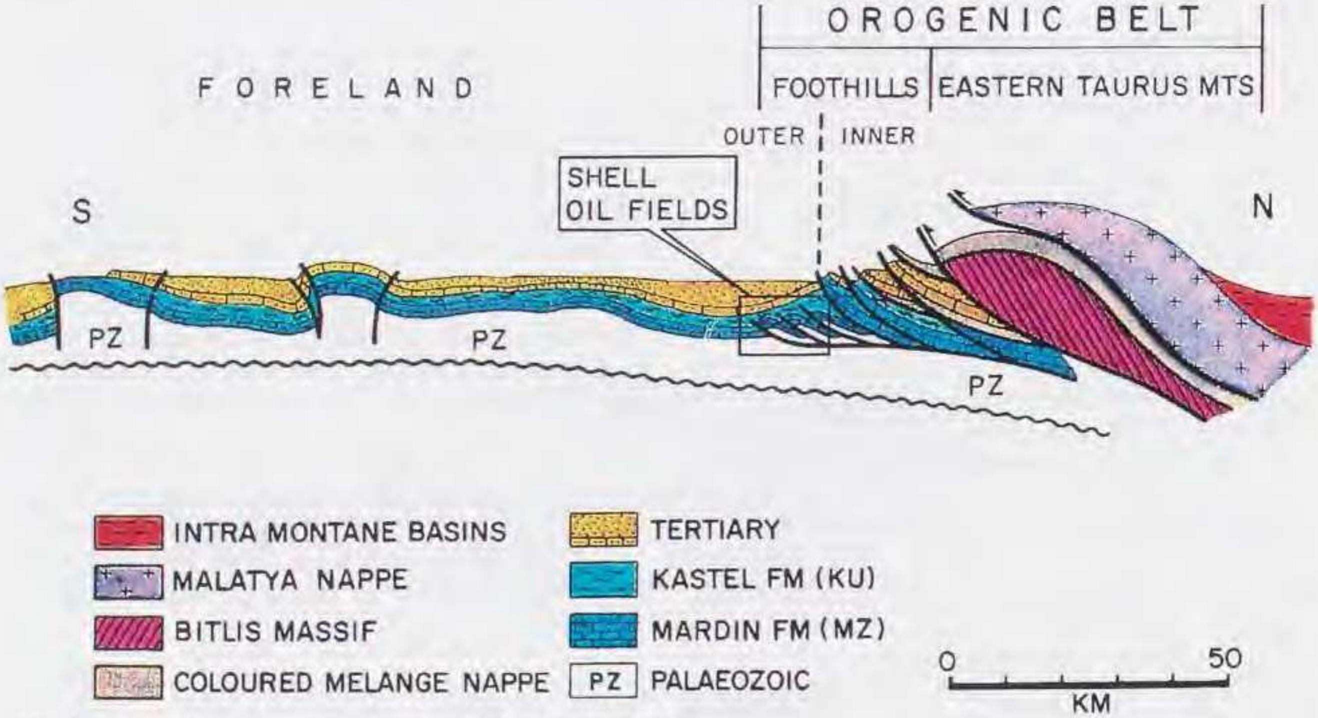

FIG. 6. Schematic cross-section, Southeast Turkey orogenic belt

Following the emplacement of the ophiolitic nappes in the Late Cretaceous, the compressional tectonic setting gave way to a predominantly extensional regime. The Foothills Belt thrust imbricates and the Foreland were buried by shallow marine sediments during the Lower Tertiary (Fig. 7d). Rapid facies variations indicate a series of changes in sealevel, reflecting continuous interaction between the Arabian Platform and Eurasia.

During the Middle Miocene the marine environment was gradually replaced by continental conditions (Fig. 7e). Yilmaz (1993) argues that this was caused by the thrusting of a metamorphic nappe complex over the northern edge of the Arabian Platform following the consumption of oceanic crust. The northern part of the Foothills Belt was the scene of imbricate thrusting (Fig. 7e) deforming the Late Cretaceous structures and their Tertiary overburden. In the southern parts of the Foothills Belt and in the Foreland, the advance of the metamorphic nappe complex led to gentle folding and reverse faulting.

The majority of the SE Turkey oil fields are found in the southern part of the Foothills Belt, within a relatively narrow zone along the Foreland margin. The stratigraphy of the area within which the NVTS oil fields are located may be summarised as follows (Fig. 8):

(1) a Lower Palaeozoic sequence overlying a Cambrian and older basement and containing incompetent Silurian shales. The latter formed the main detachment level for the overlying thrust units and represent the regional source rock interval,

(2) an Upper Palaeozoic to Upper Cretaceous sequence of competent rocks of variable thickness. The lower sequence of Devonian clastics and carbonates is unconformably overlain by Permian and Triassic clastics and carbonates which are in turn progressively eroded out to the west. The Lower Cretaceous Mardin Group succession, including dolomitised shelf carbonates, thins to the north and west. The uppermost members of the Mardin Group are absent in the structures within the NVTS Lease Areas (cf. Cater and Gillchrist, 1994),

(3) an Upper Cretaceous to Palaeocene sequence of shales and marls with intercalated flysch-type deposits (Kastel Karadut

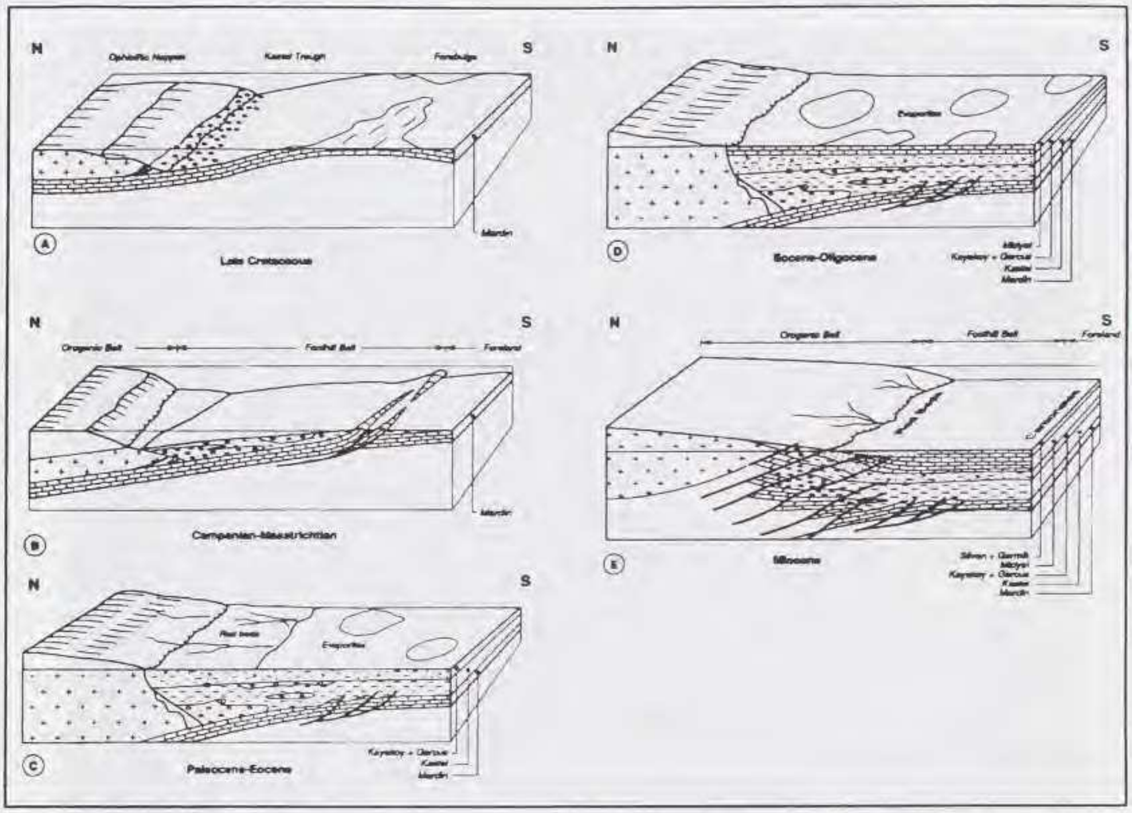

FIG. 7. Sequential development of the Southeast Turkey Foothills Belt

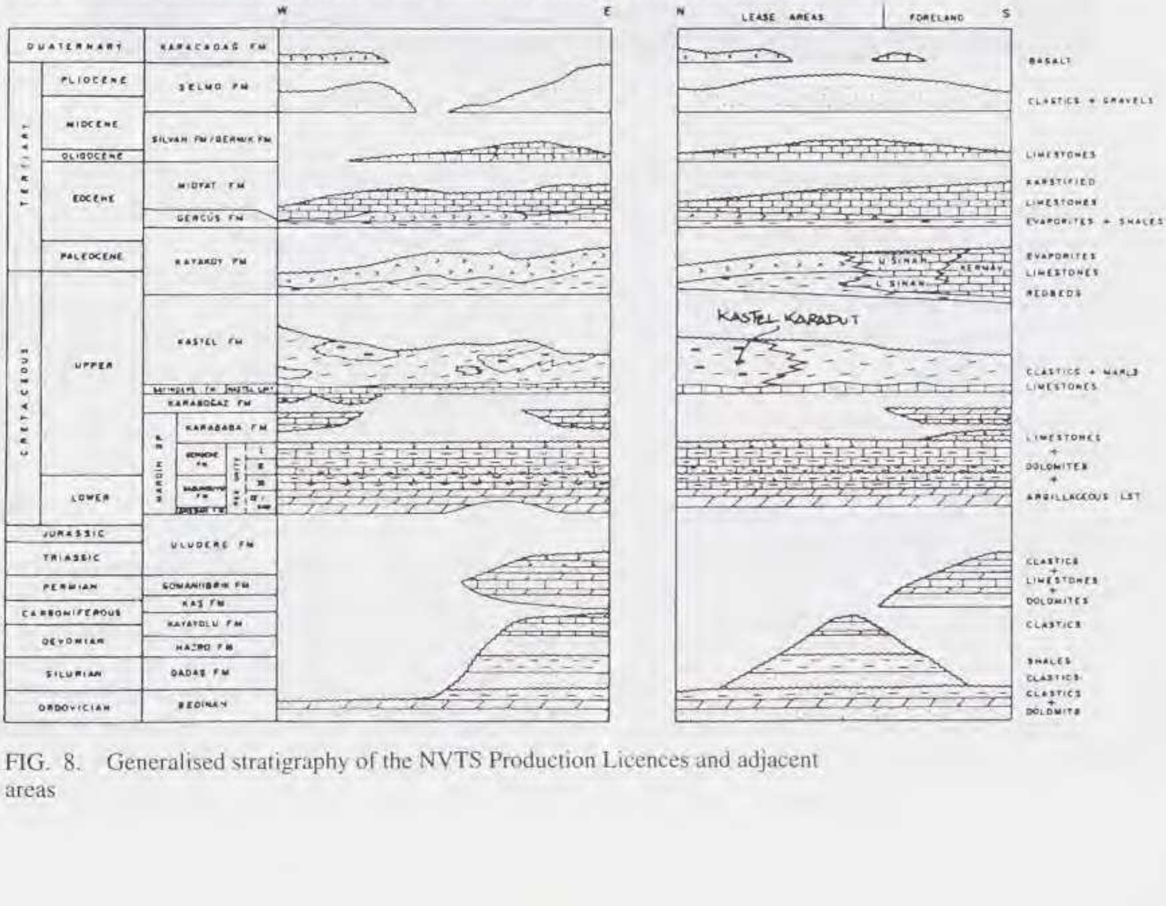

FIG. 8. Generalised stratigraphy of the NVTS Production Licences and adjacent areas

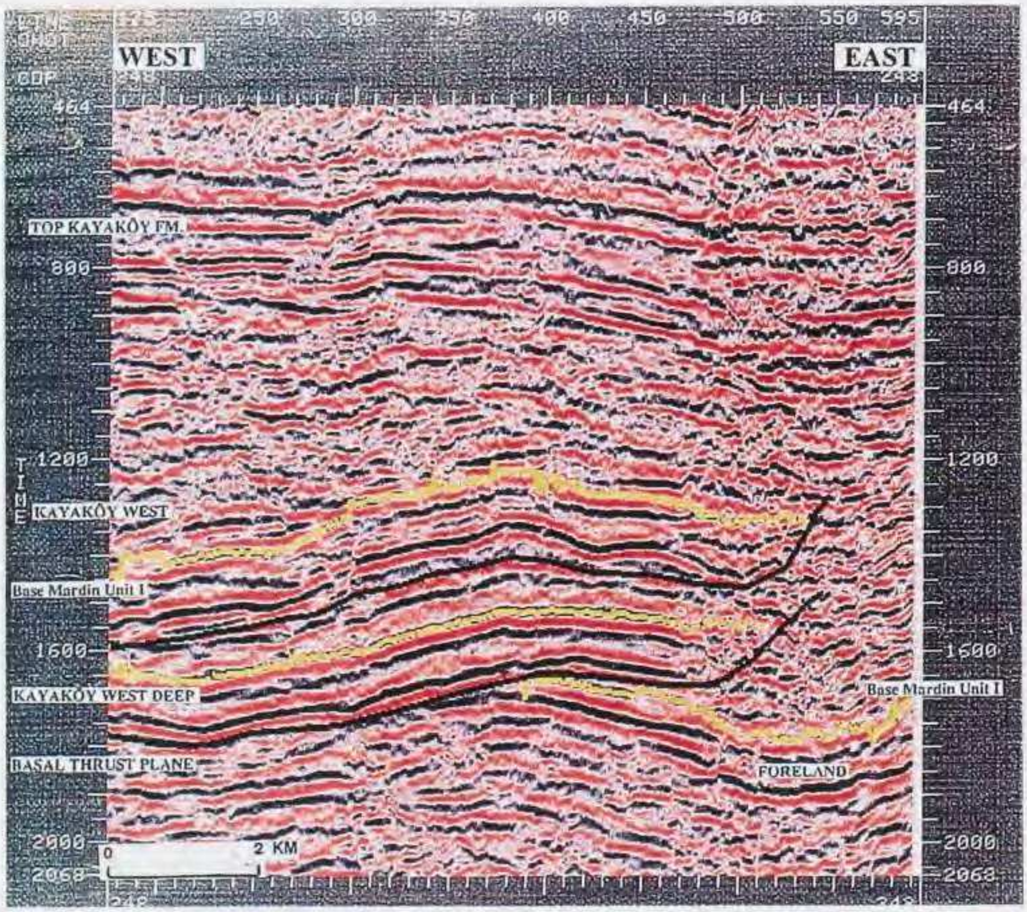

FIG. 9. Interpreted crossline 248

Facies). This thick and incompetent sequence disconformably overlies the Lower Cretaceous and thins rapidly to the west and south,

(4) a thick Eocene to Recent sequence of evaporites and shallow shelf limestones capped by basalts, unconformably overlying the Palaeocene.

DETAILED STRUCTURAL GEOLOGY OF THE NVTS LEASE AREAS

Improved 3D seismic resolution has enabled previously unseen structural detail to be recognised and relationships between the major structural units to be established. New 3D maps of most fields resemble their predecessors in gross geometry but differ fundamentally in internal detail. As discussed below, the new data has led to an overall simplification and reduction in the number of thrust sheets, combined with a radical redefinition of internal block geometries, fault patterns and inter-field relationships.

1 Western Lease Areas

Within the Western Lease Areas (Fig. 2) there are four major thrust sheets of which three have been mapped in detail. From bottom to top these sheets are: Kayakoy West Deep, Beykan -Kayakoy West -Kurkan South and Kurkan -Sincan. The latter is overlain by the Bozalan -Satyan structure, as yet not remapped.

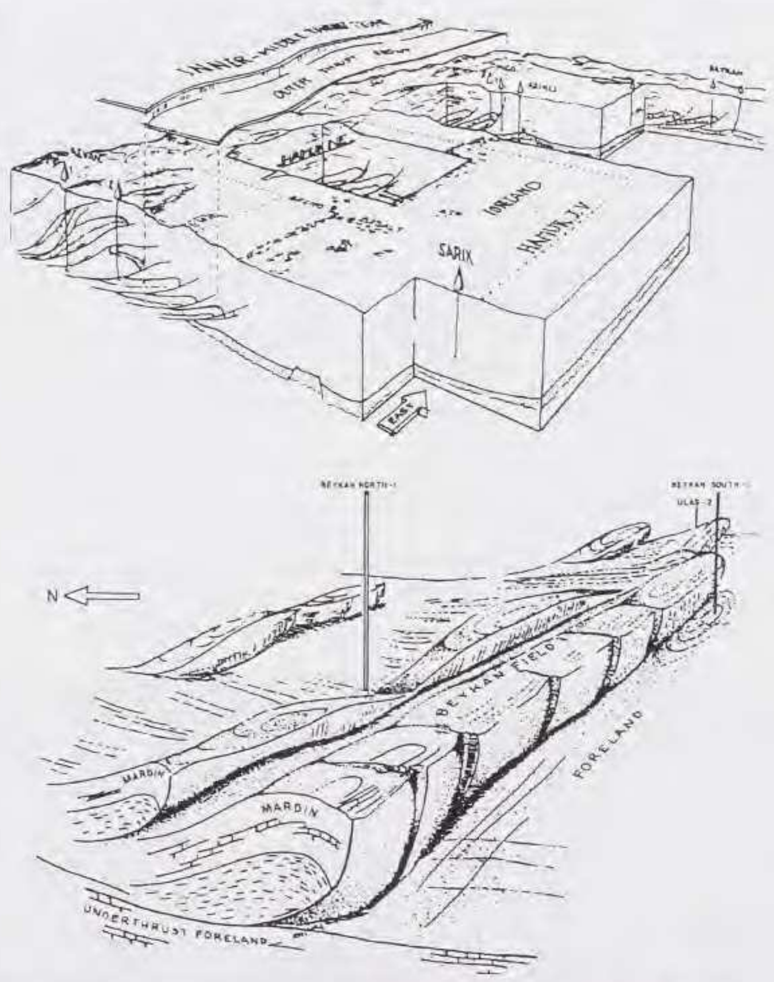

FIG. 10. Historical 3D models of Southeast Turkey, Foothills Belt structures

1.1 Kayakoy West Deep Structure

The Kayakoy West Deep field is the deepest producing structure within the Western Lease Area. Due to the poor 2D quality and the heavily dip-biased nature of the 2D grid, the structure remained poorly understood.

Following 3D interpretation the structure is now interpreted as an elongated E-W trending structure. In its central and eastern portions the structure represents a typical thrust-bound anticlinal structure with the leading edge overhanging the foreland sequence by several hundred metres. It is bounded in the north by the basal thrust of the overlying Kayakoy West structure by which it is directly overlain (in the east the structure is underlain by the foreland) (Fig. 15).

On the western flank the frontal thrust dies out and the structure passes laterally into a low-relief monoclinal structure (Fig. 9), merging with the autochtonous foreland sequences. The throw of the frontal thrust is at a maximum in the central area of the field where the structure is broadest and has maximum relief. The foreland shows most intense deformation beneath the area of maximum thrusting.

1.2 Beykan - Kayakoy West - Kurkan South Complex

The accumulations in the Beykan -Kayakoy West -Kurkan South complex lie within a single, heavily internally faulted thrust sheet (Figs. 2 and 10). The Beykan field was discovered in 1965 and by 1992 a total of 48 wells had penetrated the structure. 2D interpretation (Fig. 11) delineated an elongate thrust-bound, E-W trending anticlinal structure, internally cut by a number of E-W trending normal faults densest within the structural culmination (Fig. 14).

Interpretation of the Beykan 3D survey has shown that the Beykan field consists of an elongate thrust structure which is densely faulted, particularly on its steeper northern flank (Figs. 12 and 14). In addition to the classical compression related fault and fold features identified throughout the Foothills Belt, a complex series of cross cutting elements have been identified. The leading edge of the field is no longer mapped as smoothly cuspate, but instead is interpreted to be sinuous, complex and intersected by numerous discrete crestal faults.

Internal deformation within the Beykan structure comprises both normal and reverse faults, with numerous splays branching off the field-bounding thrust. Well-expressed backthrusting affects the flank of the field. Some of the crestal faults are oblique to the main axis of folding and appear to constitute conjugate sets. In addition to the crestal features the field is cut by two sets of steep, near N-S trending reverse faults which effectively compartmentalise the structure (Fig. 14).

The Baysu, Bektas, Kurkan South, Sahaban, Yesildere and Kayakoy West oil fields are located within the Kayakoy West -Kurkan South structure (Figs. 2 and 15). These accumulations share a common oil-water contact (OWC) at 1020 m subsea

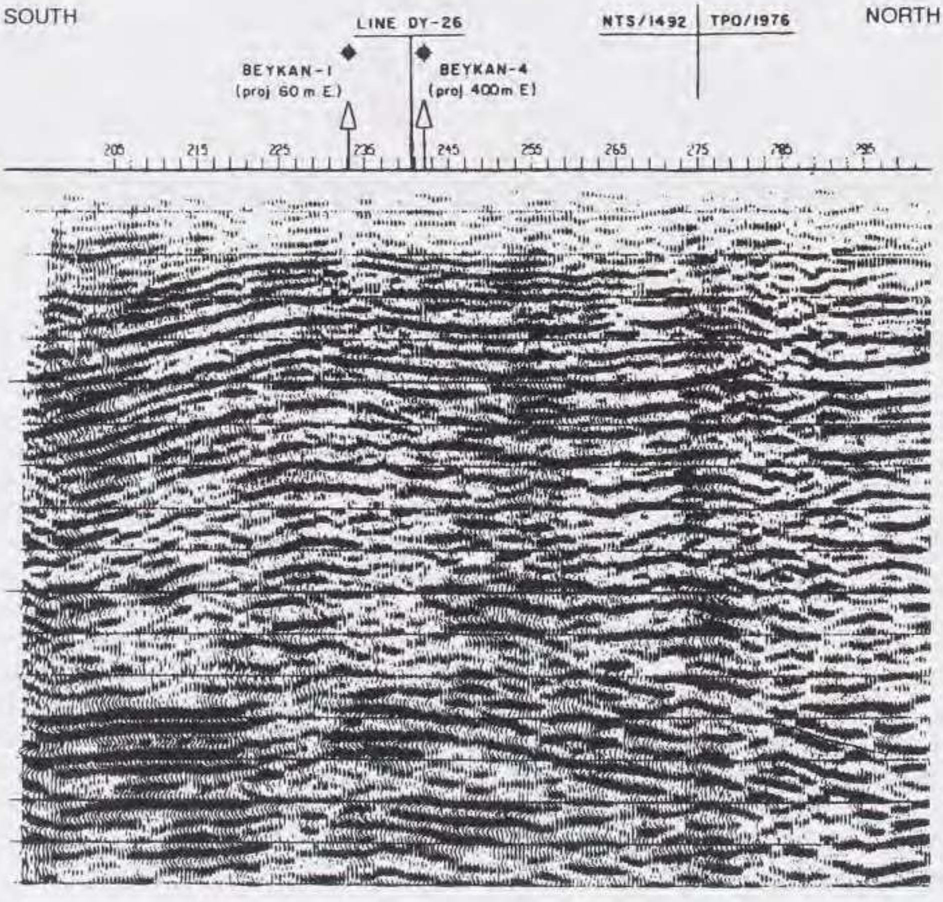

FIG. 11. 2D line DY-17 over the Beykan Field

although the controlling mechanism was not identified prior to 3D seismic acquisition. Following 3D interpretation, delineation of several of these fields and the distribution of oil within the Kayakoy West -Kurkan South complex was significantly altered. Instead of a series of relatively small cuspate structures separated by thrust faults, the sheet is now seen to comprise a single larger accumulation, combining the Kayakoy West, Kurkan South, Yesildere and Sahaban fields. It is connected to two satellite blocks forming the Bektas and Baysu fields (Fig. 16).

This large, single thrust sheet is bounded to the south by a frontal thrust and internally crosscut by several fault sets. These consist of numerous shorter, oblique reverse faults, predominantly trending WNW-ESE, with a secondary conjugate set trending ENE-WSW. In the southwestern area of the thrust sheet, well developed backthrusting is oriented sub-parallel to the frontal thrust.

1.3 Kurkan - Sincan Complex

The Kurkan accumulation is the second largest producing field in the NVTS Lease Areas and consists of an elongate thrust-bound anticlinal structure which has been subdivided into the Kurkan and Sincan oil fields (Figs. 2 and 15). The structure has been penetrated by 48 wells and was historically interpreted as a relatively unfaulted imbricate structure with the culmination located in the southwest of the field.

The gross geometry of the fields following 3D interpretation is broadly similar to previous interpretations. However, the structure is interpreted to be considerably more heavily faulted than previously realised. Faulting is predominantly reverse with fault planes often sub-vertical. The dominant fault trend is ENE-WSW with a less prominent conjugate set trending ESE-WNW. A smaller num-

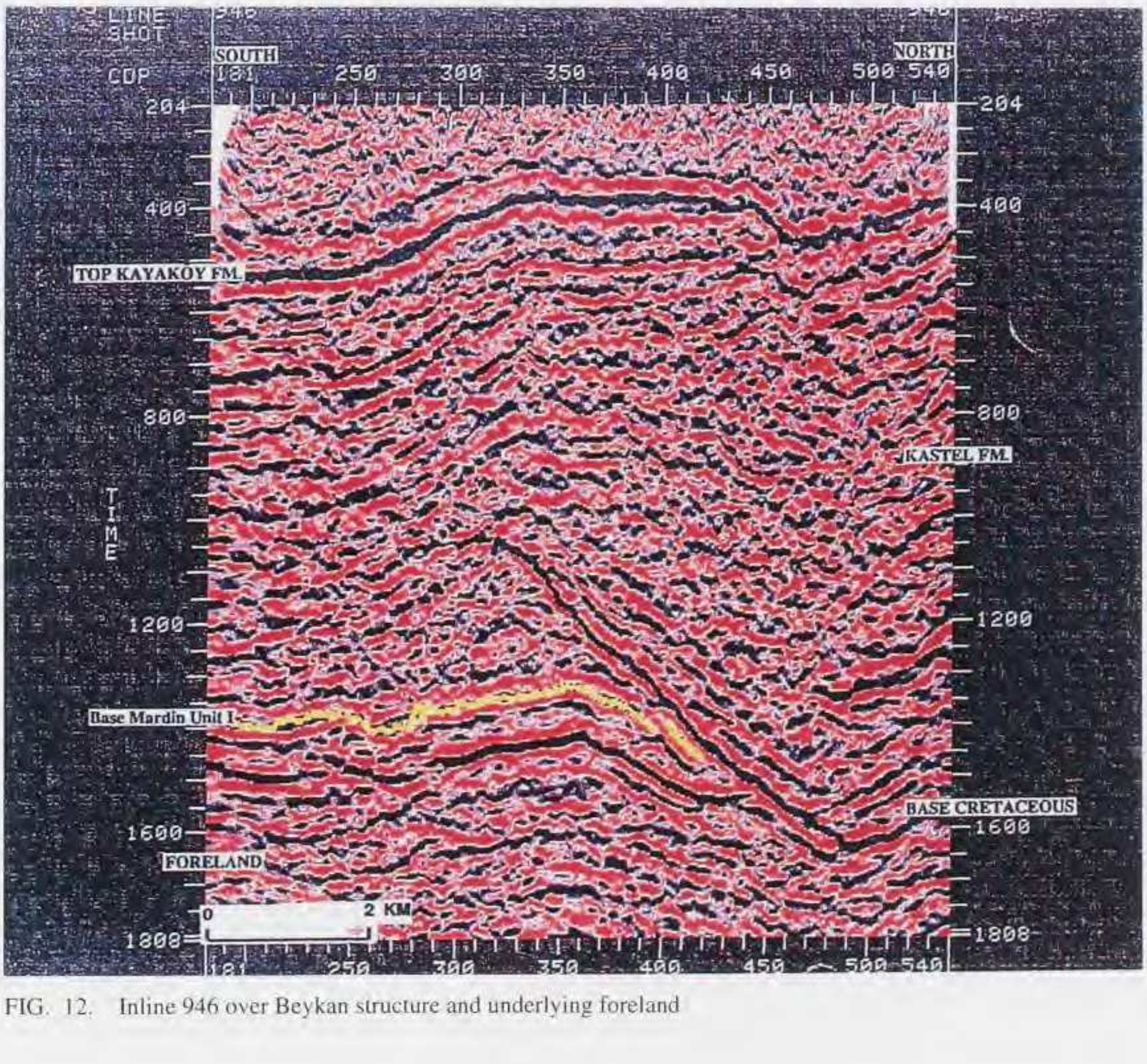

FIG. 12. Inline 946 over Beykan structure and underlying foreland

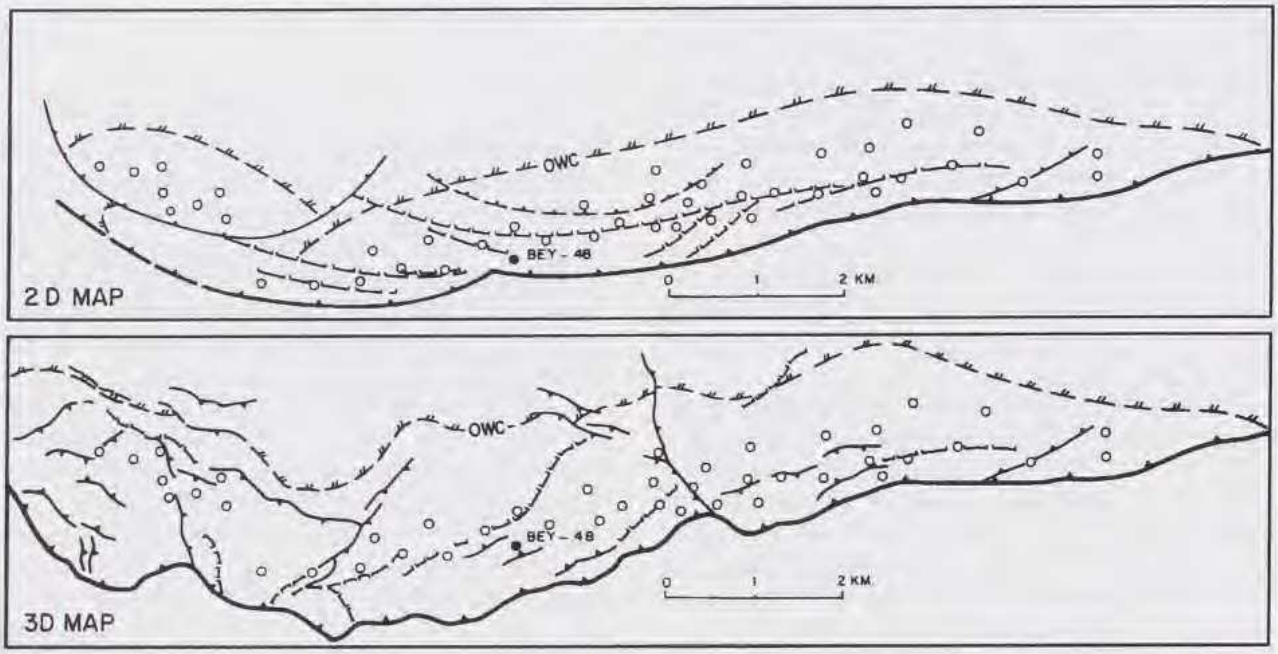

FIG. 13. Beykan Field summary maps. Pre-, and post-3D interpretation.

ber of faults trend either N-S (i.e. near perpendicular to the main thrust), or E-W forming backthrusts. The leading edge of the structure is a sinuous surface, locally offset by intersecting faults.

The culmination on the southwestern edge of the structure is adjacent to a major sidewall ramp (Fig. 17). The Top Mardin surface plunges some 350 m deeper to the west of this ramp. It is likely that more intense buckling related to thrusting over this sidewall ramp was responsible for the presence of larger faults in the western part of the Kurkan field.

2 Eastern Lease Areas

In the Eastern Lease Area (Fig. 2) two major thrust sheets are present (Katin -Barbes, and the overlying sheet making up the fields of the Northern Trend). The poorly developed Caytepe feature to the south may be an incipient thrust structure but seems to have more affinities with the foreland setting.

2.1 Katin - Barbes Structure

The Katin-Barbes imbricate is structurally rather simple, consisting of two thrust-bound anticlinal structures, separated by a saddle (Fig. 2.). The crestal area is relatively tightly folded and the northern flank dips at 25-40°, progressively steeper towards the west (Fig. 18). A deeper Palaeozoic gas-condensate accumulation is located within the same thrust sheet, almost directly above the decollement level. Within the Mardin resevoir in the Katin-Barbes oil field, faulting is predominantly parallel to the thrust front, consisting of a combination of concave upwards cuspate, south hading backthrusts and lower angle normal faults on the northern flank (Fig. 19). On the eastern margin of the Barbes structure the frontal thrust passes laterally into a sidewall ramp, the thrusted Mardin sequence merging with the foreland (Fig. 20).

To the north and overlying the Barbes field, the Kastel sequence with abundant Karadut facies sediments, has also been involved in thrusting and a complex series of intra-Kastel Formation unconformities, slumps and onlapping relationships may be identified.

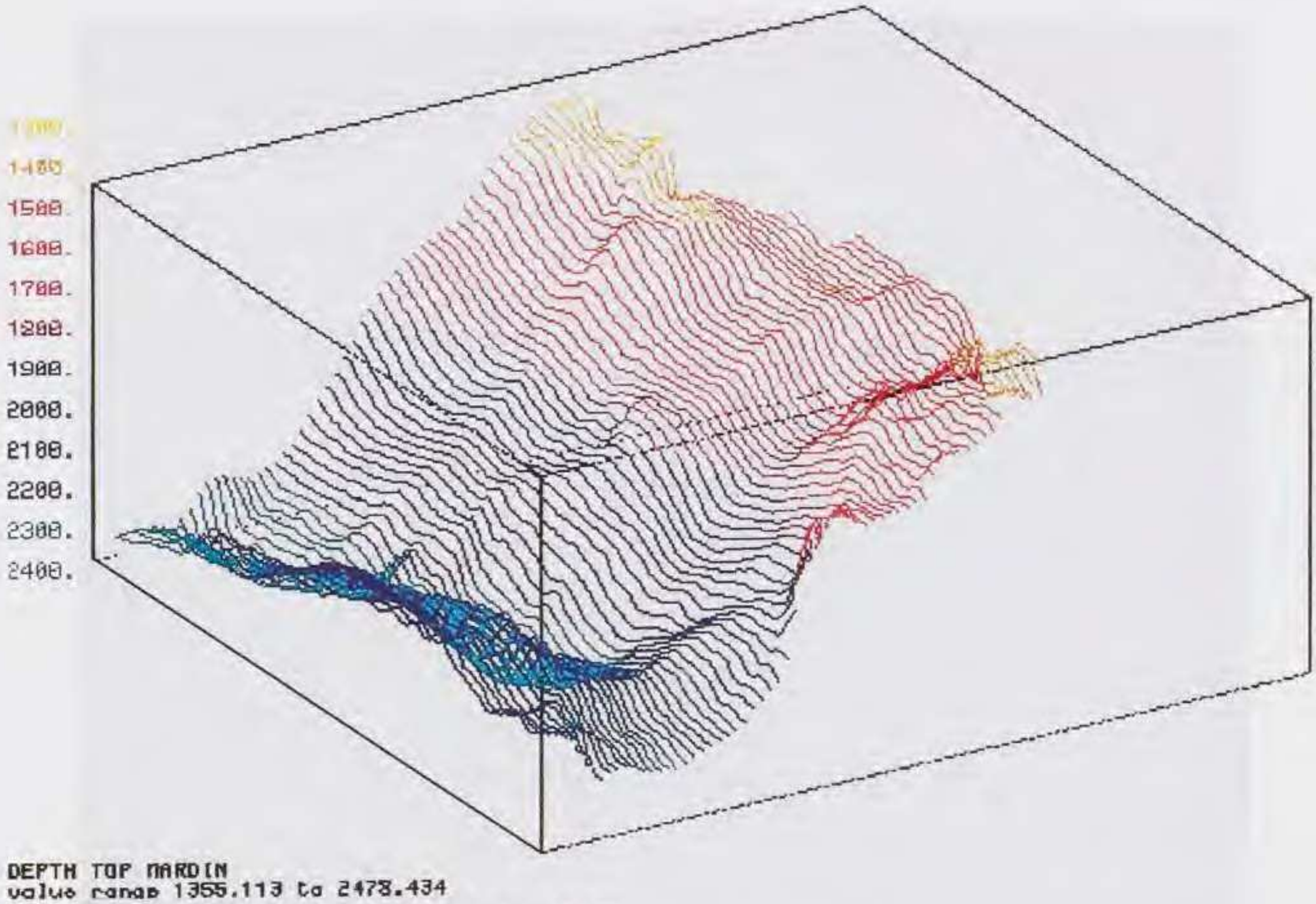

FIG. 14. Isonmetric display Beykan Field viewed from WNW.

3 Foreland Areas

In contrast with the large number of wells within the thrust structures situated directly to the north, the number of wells penetrating the autochtonous Mardin sequence of the foreland within the Lease Areas is small (Figs. 6, 10 and 12). Although hydrocarbons shows were encountered in some of these wells, producible quantities of oil have not been found to date.

The foreland area south of the Beykan Field has previously been mapped as being largely undeformed. The foreland Mardin Group was penetrated in two deep, dry Beykan wells. Oil was, however, produced on test from the exploration well Beykan South-1. Footwall deformation leading to the formation of potential traps, was not previously observed on 2D data largely as a consequence of the poor data quality beneath the overhanging Beykan structure (Fig. 11). 3D data however, shows that foreland deformation is more complex and intense. The foreland underlying the Beykan Field can be seen to be deformed and a low relief footwall ramp anticline is interpreted to have formed immediately beneath the Beykan structure (Fig. 12).

The 3D azimuth map of the foreland area south of Kayakoy West and Kayakoy West Deep shows the Top Mardin Group surface to be cut by two main fault sets (Fig. 18). Close to the intersection with the frontal thrust (effectively the northern margin of the foreland), a series of reverse faults are interpreted. These faults (possibly incipient thrusts) are parallel to the thrust front, their spacing decreasing northwards into the footwall. A second set of predominantly reverse faults is aligned near-orthogonal to the first set. The orientation of these faults seems to rotate from N-S in the west to NNW-SSE in the east of the survey area, (i.e.

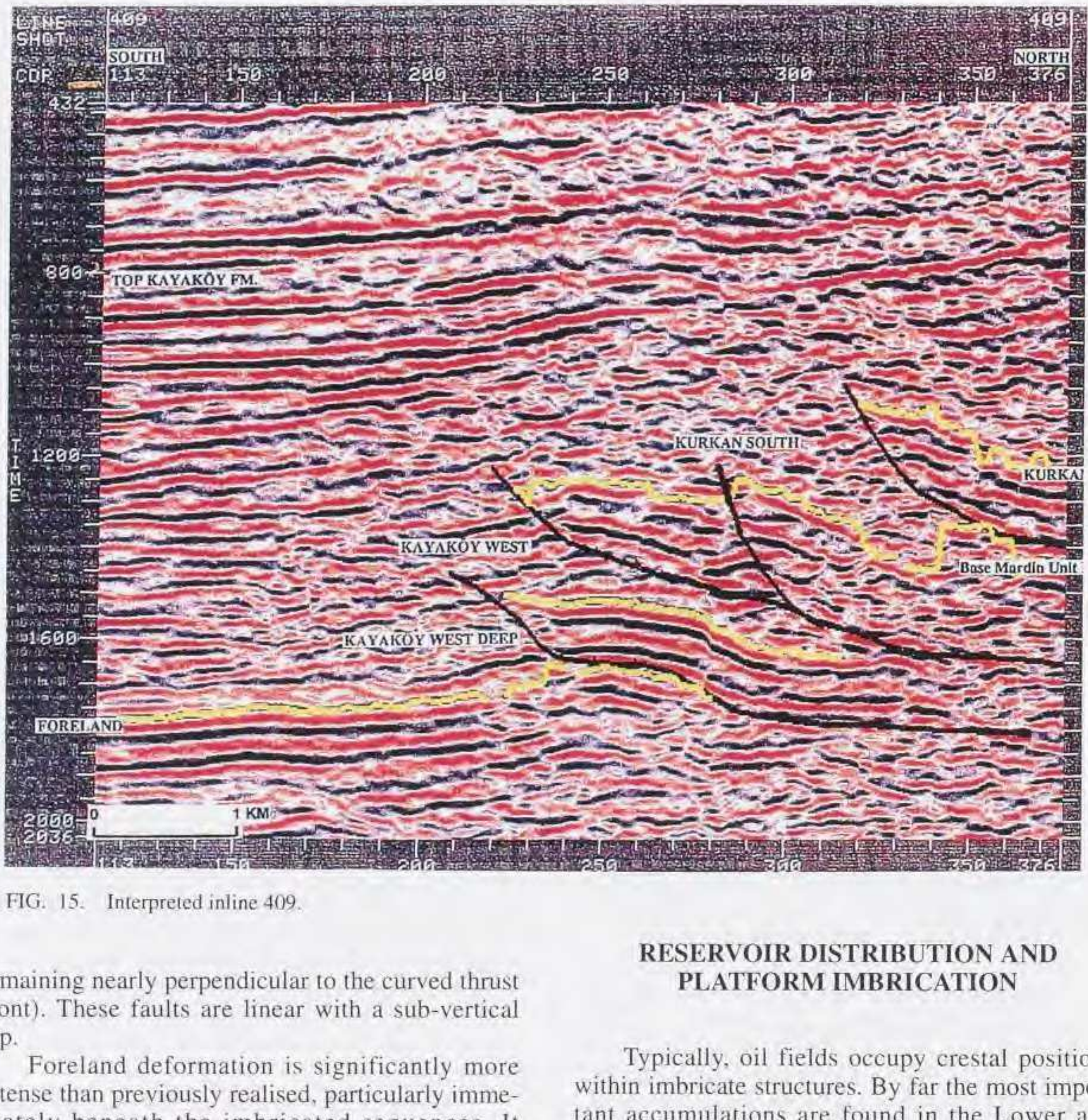

FIG. 15. Interpreted inline 409.

remaining nearly perpendicular to the curved thrust front). These faults are linear with a sub-vertical dip.

Foreland deformation is significantly more intense than previously realised, particularly immediately beneath the imbricated sequences. It appears that the deformational effects in the foreland of the thrusted overburden are restricted to an area within 1-2 km of the fault plane/foreland intersection. Beyond this zone both the intensity of faulting and folding decreases rapidly until the dominant faults appear to be near N-S lineations interpreted as incipient or aborted sidewall ramps.

RESERVOIR DISTRIBUTION AND PLATFORM IMBRICATION

Typically, oil fields occupy crestal positions within imbricate structures. By far the most important accumulations are found in the Lower and Upper Cretaceous carbonates of the Mardin Group. The best reservoir rocks are dolomites with secondary intercrystalline porosity and grain supported limestones (Cordey and Demirmen, 1971; Cater and Gillchrist, 1994). Upper Palaeozoic sandstones also act as reservoir rocks in the imbricates in the east. The carbonates of the Kastel Formation form the top seal.

The better Mardin reservoirs were formed by diagenetic processes which caused the formation of dolomites. Dolomitisation cross-cuts stratification

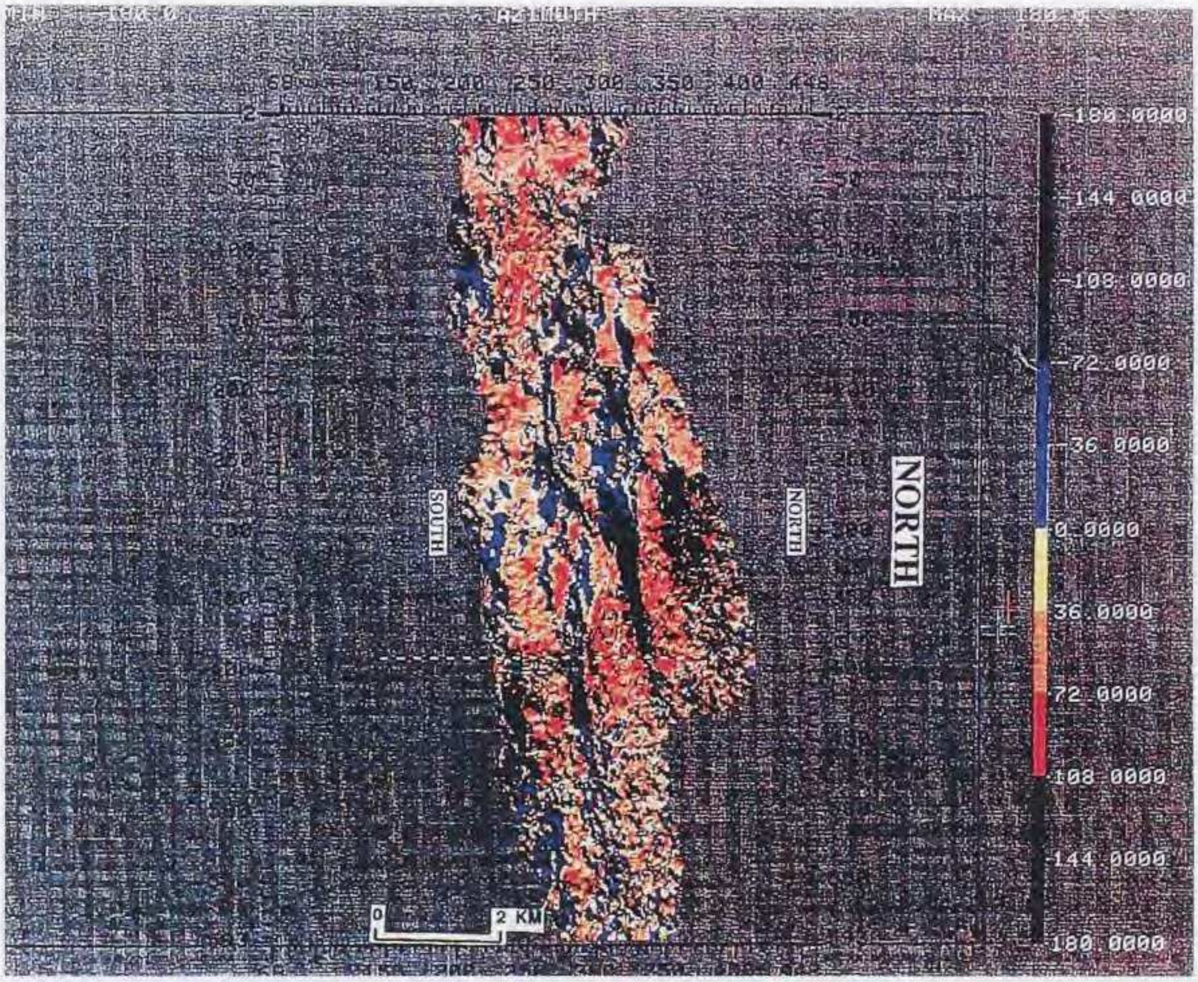

FIG. 16. Azimuth map, base Mardin unit I, Kurkan south-Kayakov west.

and is variable in thickness (Cordey and Demirmen, 1971; Cater and Gillchrist, 1994). The presence of thick dolomites within the oil fields area contrasts with both the foreland setting to the south and the thrusted sequence of the Foothills Belt to the north. The results of some 25 exploration wells in these areas demonstrate that dolomite development in the Upper Mardin sequence is very limited or entirely absent.

Within the Beykan field dolomites in the Upper Mardin sequence seem to be primarily developed in an area parallel, but slightly offset to the north of the field culmination. There is evidence that this relationship exists in analogous imbricate structures. This spatial distribution of dolomites, combined with the observation of evidence for subaerial exposure led to the conclusion that the terranes presently incorporated in the imbricated zone formed a positive area during the deposition of the uppermost Mardin Group in the Late Cretaceous (Cordey and Demirmen, 1971).

Imbrication of the platform margin occurred during the deposition of the complex sequences of the Kastel Formation (Fig. 21). The preferentially dolomitised areas, related to crestal areas in individual structures, seems to imply that the location of the eventual breakthrough of the basal thrust plane coincided with the Mardin Forebulge Area. The deformational history is complex, some structures forming as folds prior to imbrication while others imbricated without appreciable folding.

As a result of the continuous growth of the Mardin structures, reworking of the Kastel Karadut sediments (Fig. 8) occurred. Kastel Formation sediments on the crests of the imbricating structures were eroded and redeposited as clastic wedges at the leading edges of the imbricates. Eventually, Karadut sedimentation was restricted to the deep-

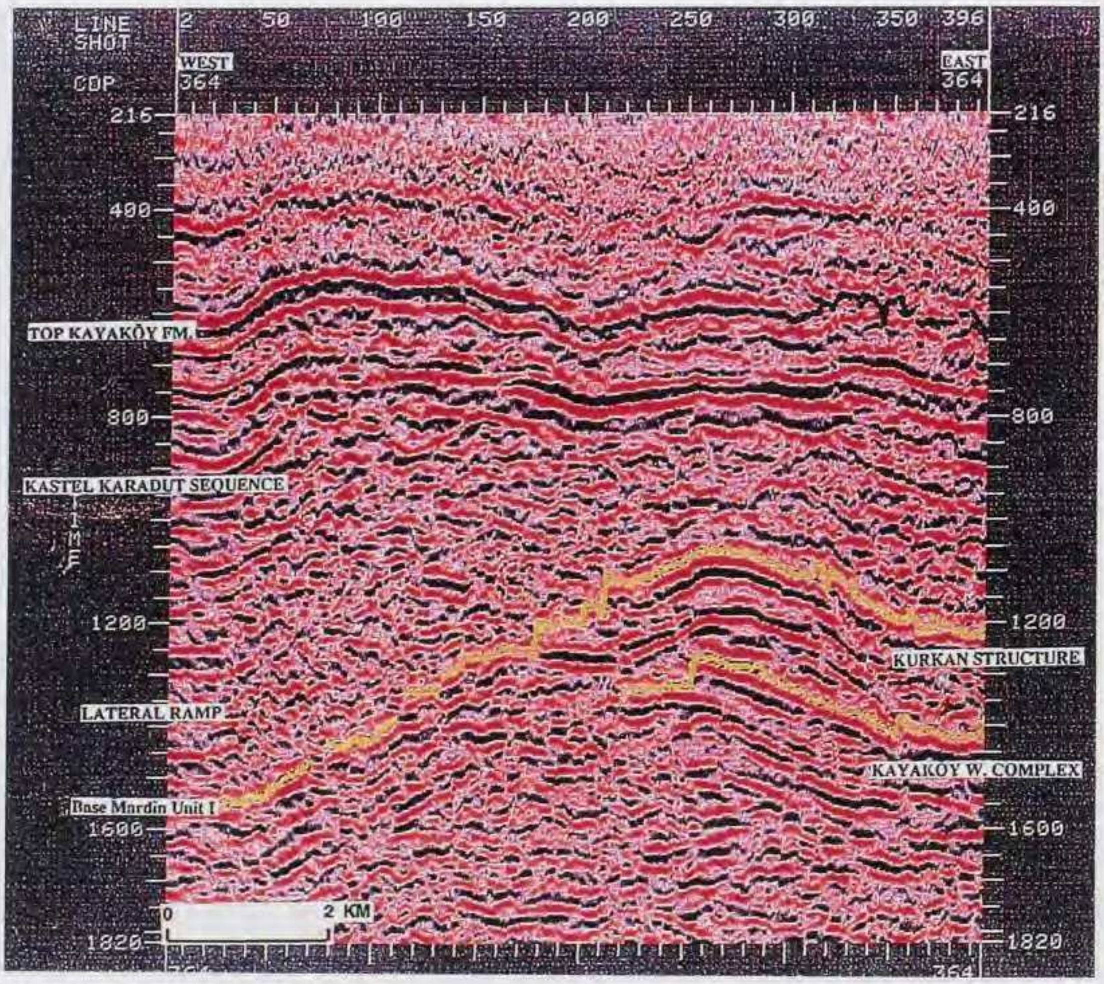

FIG. 17. Crossline 364 showing lateral ramp on Kurkan flank.

ening trough between the imbricated platform edge and the orogenic belt in the north. The Karadut complex reached an ultimate thickness of over 2000 m (including tectonic repetitions) to the north of the production licences. To the south the imbricated zone at the platform edge must have formed an effective barrier to Karadut sedimentation. This is supported by the virtual absence of Karadut sediments in the Foreland.

OIL MIGRATION PATHS AND FIELD FLUID CONTACTS

The oil produced from the Foothills Belt oil fields has been generated from thick marine Silurian shales of the Dadas Formation. The kitchen is interpreted to be located to the north of the producing fields, in the trough which separates the Orogenic Belt from the Foothills Belt. Oil migration probably post-dates formation of the Mardin forebulge, with the main phase of expulsion taking place during deposition of the Kastel Formation. Deposition of the upper part of this formation, ie. sediments of the Kastel Karadut facies, buried the source rocks to a depth sufficient for maturity to be reached. Expulsion probably continues to the present day.

FIG. 18. Azimuth display, base Mardin unit I forland, Kurkan extension 3D.

Despite the complexity of the thrustbelt structures, the original fluid contacts exhibit a remarkable consistency between fields.The Beykan field (Fig. 13) for example, has an OWC at 1080±20 m subsea, while the fields in the Kayakoy West - Kurkan South structure share an OWC at 1020±50 m subsea.

Following 3D mapping there is substantial evidence that fluid contacts are structurally controlled. The accumulations in the Kayakoy West - Kurkan South complex, interpreted to share a (near-)common OWC, can be demonstrated to be structurally interconnected (Fig. 23). The position of the original fluid contact is controlled by a structural spillpoint mapped between 1040 and 1100 m subsea. Spill probably follows the structural saddle between the Kayakoy West -Kurkan South complex and the Beykan field, oil eventually escaping to the north via the Kurkan western flank or an unidentified structure to the north of Beykan. The shallow Kurkan -Sincan accumulation (Fig. 3) may have been partially directly charged by hydrocarbons from the kitchen to the north, with an additional contribution from the Kayakoy West -Kurkan South complex beneath, oil migrating vertically, probably via faults, through the ramp beneath the Kurkan structure.

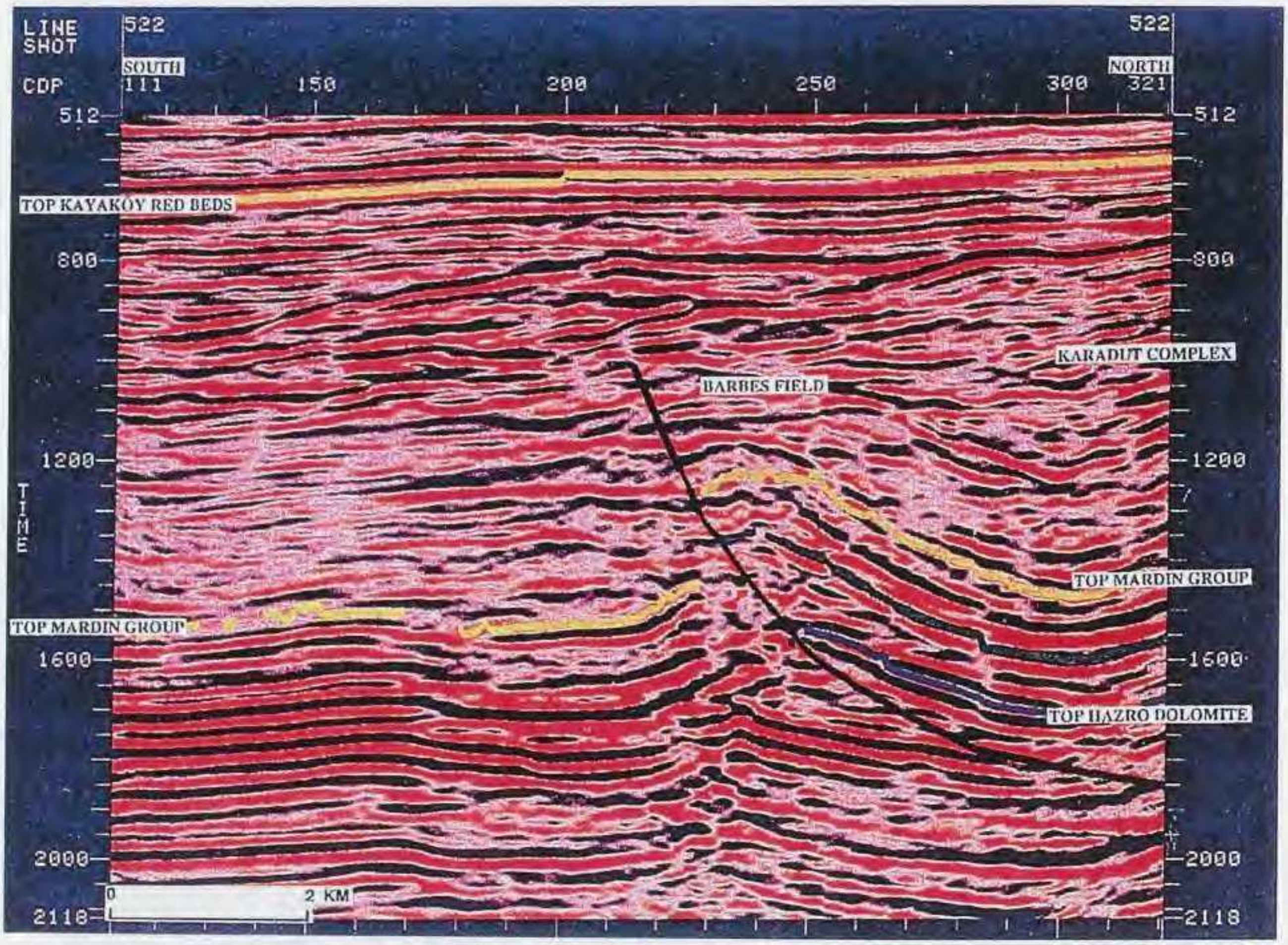

FIG. 19. N-S line 522, Katin-Barbes 3D

KINEMATICS AND MECHANICS OF THE IMBRICATION OF THE MARDIN SEQUENCES

The producing structures on the southern edge of the SE Turkey Foothill Belt are typical examples of imbricate structures in a Foreland setting. Thrust sheets are relatively thin, comprising a layered sedimentary sequence and have a length which is several times greater than their thickness. Imbricate structures in this setting are thought to have been initiated as if they were "pushed from behind" by some tectonic force over a decollement horizon (basal slip or detachment plane).

In the Eastern Lease Areas (Fig. 2) a clastic sequence overlies the argillaceous units of the Dadas Formation. This clastic sequence is progressively cut out to the west such that in the Beykan area the Cretaceous carbonate sequence lies almost directly on top of the basal shales (Fig. 12). The observed effect is that, in the east, imbricates are significantly thicker and contain in their basal sections a sedimentary sequence with fundamentally different mechanical properties compared to the overlying carbonates. In a mechanical sense the thrust sheets are thus composed of a relatively stiff, brittle beam of carbonates where the brittleness is enhanced by dolomitisation, underlain by an eastward thickening sequence of less brittle clastics on a weak, argillaceous substratum. The difference in thickness has traditionally been taken as the primary explanation for the difference in tectonic style. The difference in mechanical properties is probably an equally significant factor.

In the west (e.g. Beykan Area) folding took place on a smaller scale as a consequence of the

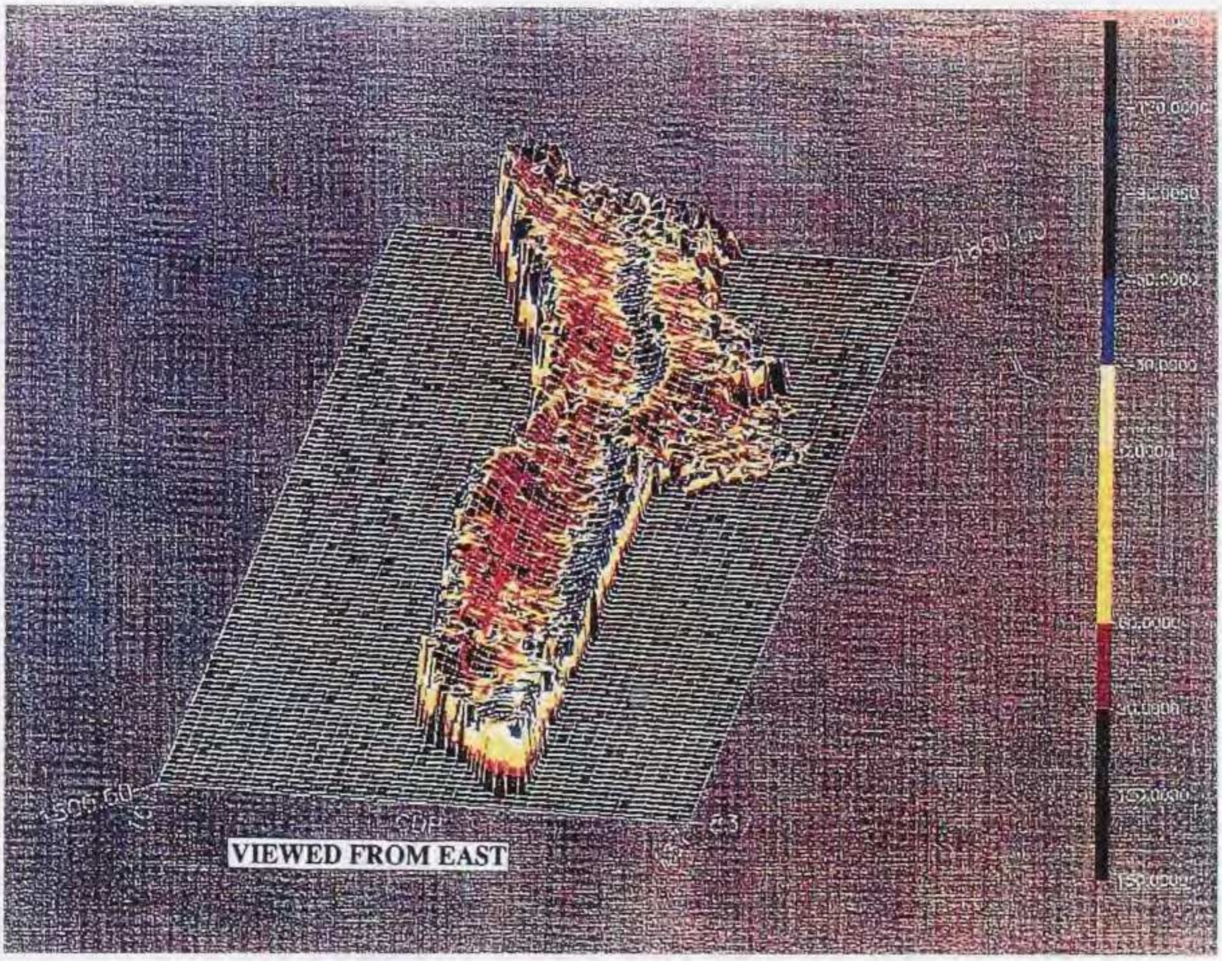

FIG. 20. Isometric display, base Mardin group, Katin-Barbes structure, with azimuth overlay.

reduced thickness of the stratigraphic section involved (Fig. 23). Initial shortening was accompanied by gentle folding, as evidenced by the low structural dips encountered in wells and on seismic. Continued shortening caused the basal thrust/slip plane within the Dadas Formation to ramp upwards through the brittle carbonate sequence of the Mardin Group and thrust the allochthonous block over the foreland (Fig. 23). In the east the increased thickness of the thrusted sequence led to larger amplitude folding and higher structural dips. Increased shortening was therefore accomodated prior to the breakthrough of the basal thrust. Folding prior to thrusting was further amplified by considerable ductile deformation of the clastic Dadas sequences within the cores of the anticlines.

The thickness of the eastern thrusted sequence must have caused vertical loading on the basal slip plane to be higher compared to that of the thinner western sequence. The likely effect was that, with a higher load, the frictional characteristics along the basal slip plane changed and hindered the movement of the thrust sheet (Goff and Wiltschko, 1992). Finite element analysis of tapered thrust models (Mäkel and Walters, 1993) has clearly demonstrated that variation in basal friction does influence the resulting geometry of imbricated structures. Reduction of friction, either by changing characteristics of the rock involved or by increasing pore pressure, tends to result in larger thrust sheets (Mandl and Shippam, 1981).

In a mechanical sense the thrust sheets of the Kurkan, Kayakoy and Kayakoy West structures (Fig. 17) resemble that of the Beykan structure, i.e. thin Dadas sequence and relatively gentle folding. However, in contrast with Beykan where the deformation resulted in one large imbricate structure,

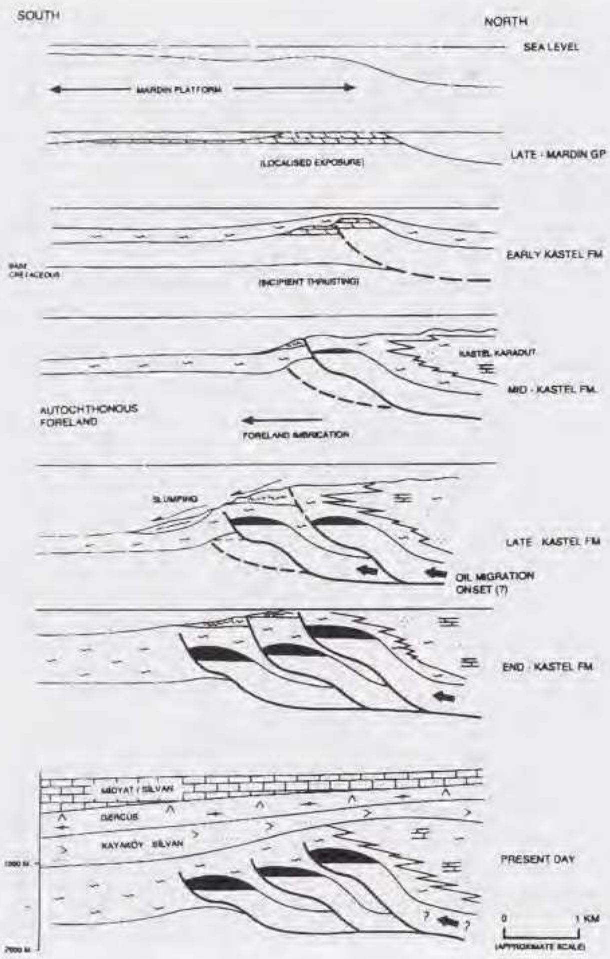

FIG. 21. Schematic evolution of NVTS Lease Areas oilfields.

the Kayakoy West area consists of a stack of smaller imbricate structures (Fig. 24). Since differences in slab thickness are not apparent, the changes are interpreted to relate to greater friction along the basal slip plane beneath the Kayakoy West area compared to the Beykan structure. Little data is available on the composition of the rock within the slip plane. Relatively minor differences in the composition of the slip plane rocks, e.g. an increased presence of siltier material, could be responsible for increased friction (Goff and Wiltschko, 1992).

The last parameter which may have influenced the geometry of the structures is the shape of the footwall ramp, which in turn affected friction on the basal thrust plane. As a result of propagation of the basal slip plane ahead of the leading imbricate (Mäkel and Walters, 1993), subsequent foreland deformation may have been superimposed upon structuration which predated the main compressional phase. Pre-existing faults in the foreland sequences may have caused the formation of sidewall ramps within the thrust sheets. Indeed in the Beykan and Kayakoy West areas (Fig. 18) there is evidence to support this. Thus, the geometry of the footwall, in combination with frictional behaviour along the slip plane, was most likely responsible for the observed differences in the deformational styles of the individual thrust sheets.

The geometries of the Kurkan and Kayakoy West structures (Fig. 3) and the influence of basal friction during their creation conform with the classical interpretation of foreland propagation of

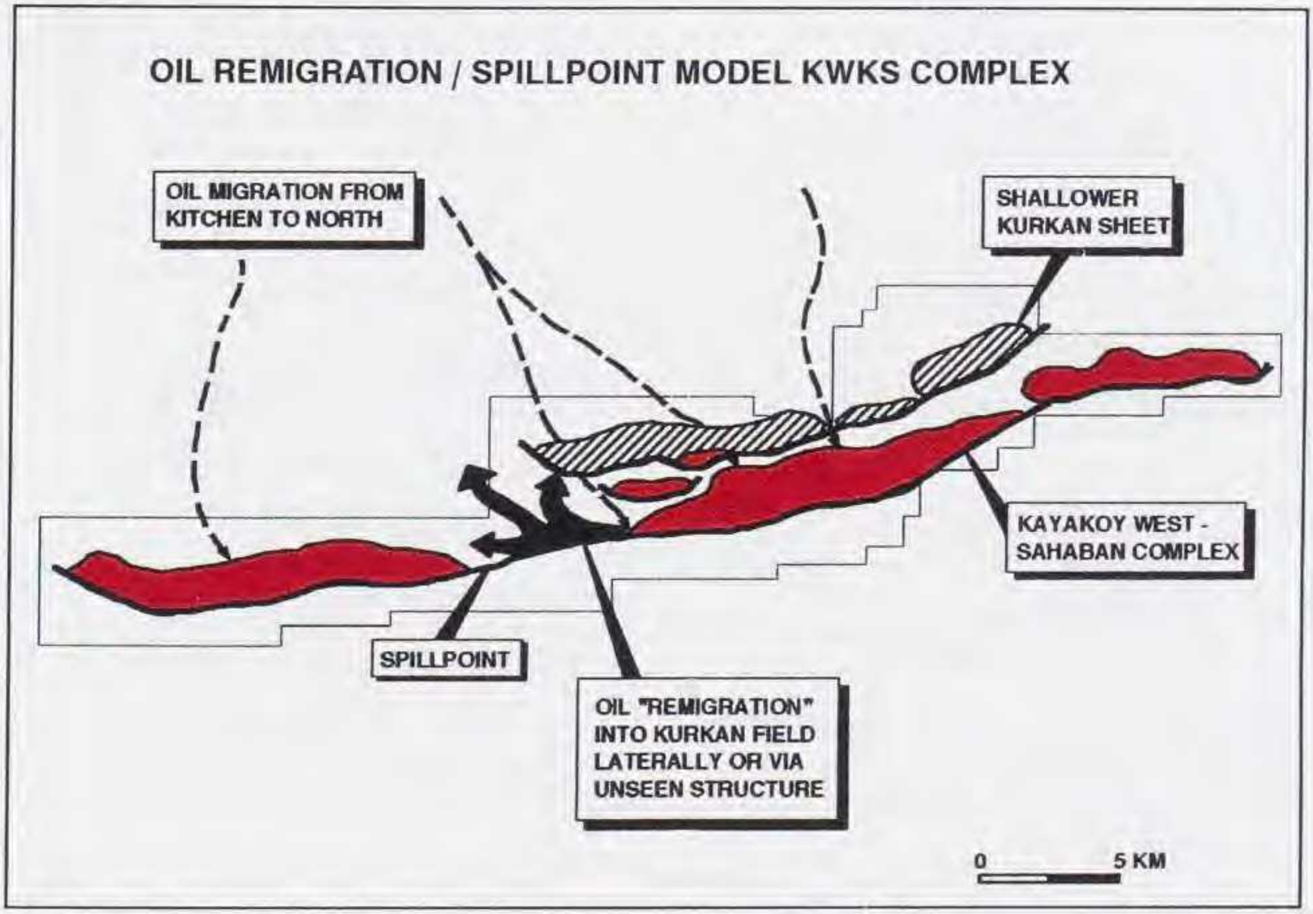

FIG. 22.

imbrication. This implies that the imbricate closest to the hinterland forms first where a steep thrust intersects the basal slip plane (Mäkel and Walters, 1993). When the imbricate overrides the foreland, the stress regime and hence the deformation in the footwall adjusts itself to the compressional force and the load exerted by the imbricate. The location of the next imbricate then depends primarily upon the mass of the overriding thrust sheet and the frictional characteristics along the basal slip plane. In principle, a higher load and higher friction will lead to shorter imbricates (Mandl and Shippam, 1981; Goff and Wiltschko, 1992).

The formation of the second imbricate will tend to steepen the first (Li Huiqi et al., 1992). Indeed the Kurkan structure seems to have a much steeper northern flank than the underlying Kayakoy West structure (Fig. 15). The Kayakoy West Deep structure (Figs. 9 and 15), overrides the foreland in the east but in the west is still connected to the foreland through a transfer zone expressed as a monocline. Thus it seems that Kayakoy West Deep is partly an incipient thrust structure. It was most likely formed after the Kayakoy West structure was pushed over a footwall ramp, but the next imbricate (Kayakoy West Deep) failed to complete its development. Indeed the evidence from other areas (e.g. Beykan and the Caytepe structure in the Eastern Lease Area) seems to indicate that foreland imbrication was the dominant process.

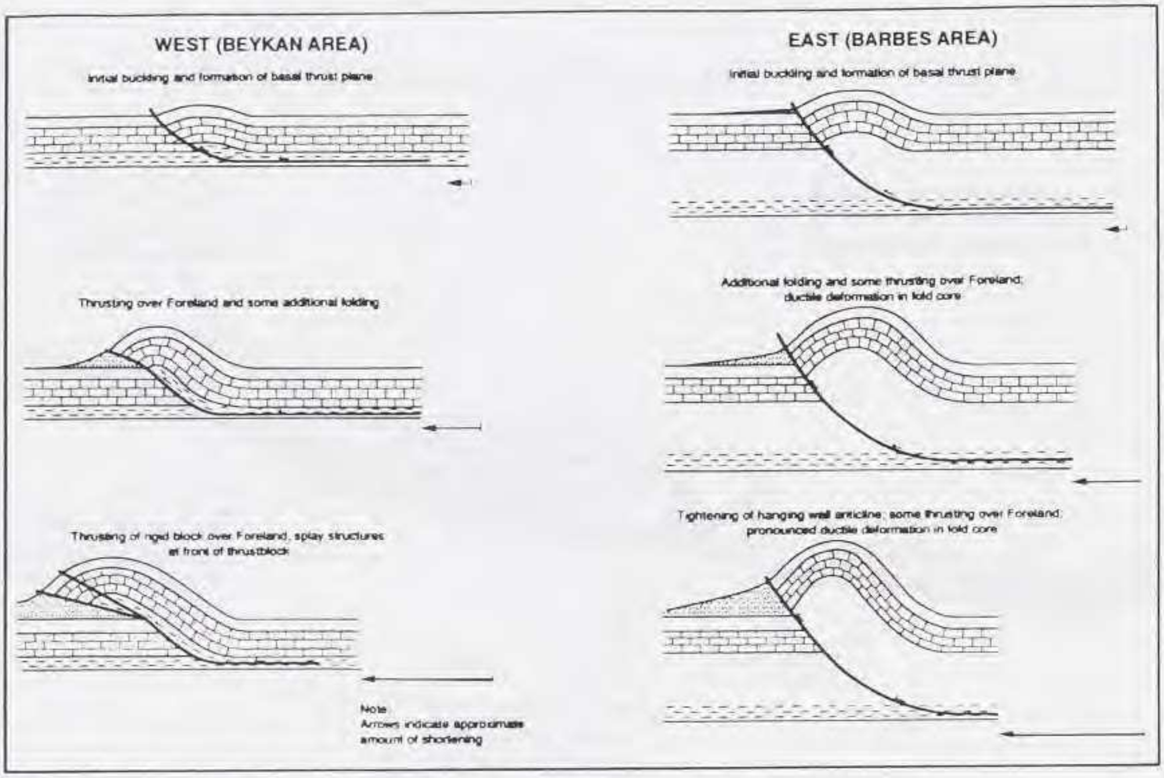

FIG. 23. Influence of stratigraphic thickness and rock properties on imbricate geometry.

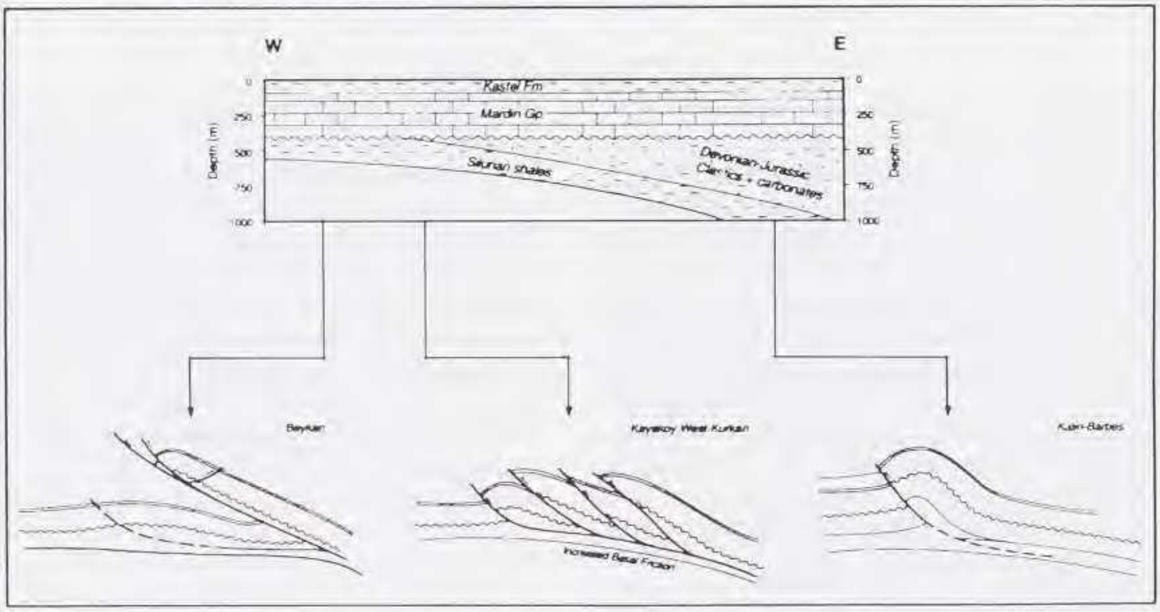

FIG. 24. Difference in imbricate geometry as a result of stratigraphic thickness and frictional properties.

POTENTIAL IMPACT OF 3D RESULTS ON APPRAISAL AND DEVELOPMENT IN SE TURKEY

The results to date of the acquisition of 3D seismic in the SE Turkey thrustbelt can be summarised as follows.

(1) 3D seismic data has been demonstrated to substantially improve the delineation of subsurface structures compared with previous 2D results. Definition of internal faulting and fault block boundaries, identification of the interconnectivity of producing fields and correlation of major faults have been radically improved. This has also positively impacted upon the general understanding of how these structures formed and the parameters which influenced their ultimate geometries,

(2) 3D results have led to fundamental revisions of structural maps in both heavily drilled (Beykan) and lightly explored (foreland, Kayakoy West Deep) areas. Interpretation of previously unseen attic areas have been demonstrated in several mature fields and the new structural maps are likely to provide a basic framework for future reservoir characterisation work.

Acknowledgements - The authors wish to thank *NV Turkse Shell* for permission to publish these results. The interpretation of the seismic data represents our personal views and subsequent work may have resulted in refinements to the subsurface model. Many thanks to Rifat Güler for draughting the enclosures, to our former colleagues in production geology and exploration in *NVTS* for providing additional material and constructive criticism, and to Alf Garnett who provided the Katin -Barbes 3D material.

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